FTTCP: Fault Tolerant Two-level Clustering Protocol for WSN

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Abstract— **In this paper, we propose an agreement-based fault detection and recovery protocol for cluster head (CH) in wireless sensor networks (WSNs) of two level cluster hierarchy. The aim of protocol is to accurately detect CH failure to avoid unnecessary energy consumption caused by a mistaken detection process. For this, it allows each cluster member to detect its CH failure independently. Cluster members employ distributed agreement protocol to reach an agreement on failure of the CH among multiple cluster members. The detection process runs concurrently with normal network operation by periodically performing a distributed detection process at each cluster member To reduce energy consumption, it makes use of heartbeat messages sent periodically by a CH for fault detection. Simulation results show, our protocol provides high detection accuracy because of agreement protocol.**

Keywords—**Wireless Sensor Network, Clustering, Fault detection, Agreement protocol, Detection accuracy.**

I. INTRODUCTION

Wireless sensor networks (WSNs) consist of hundreds and even thousands of small tiny devices called sensor nodes distributed autonomously to monitor physical /environmental conditions (like temperature, sound, vibration, pressure etc); motion at different locations; industrial sensing, infrastructure protection, battlefield awareness etc. Each sensor node has sensing, computation, and wireless communication capabilities [1]. Sensor nodes sense the data and send it to base station (BS). Sensor nodes are small in size powered by small onboard batteries that store few Joules. Sensor nodes are often left unattended which makes it difficult or impossible to re-charge or replace their batteries. The cost of transmitting information is much higher than computation and hence it is necessary to reduce the number of transmissions.

In many situations, sensor nodes are organized into clusters where data collected by sensor nodes is sent to local cluster BS (e.g. CH). CH processes this data and sends it to the BS. Clustering is an effective way to reduce the number of transmissions and prolongs the life time of a network. The CH processes the data collected from all cluster members and transmits towards BS after suitable processing. Due to this, CH drains energy much faster than cluster members. The role of CH must be rotated among cluster members to prolong the life time of the network. There are number of clustering-based routing protocols proposed in literature for WSNs [2]. These protocols improve energy consumption and performance when compared to flat large-scale WSNs, but they also increase the overhead to configure and maintain the network.

Sensor nodes are prone to failure due to harsh environment. The failure of a sensor node affects the normal operation of a WSN [3].The failure of a CH makes situation even worse. In literature, number of authors have proposed fault tolerant protocols [4-7]. In this paper, we propose a fault tolerant protocol for WSN, which is based on agreement protocol.

II. RELATED WORK

Clustering is an effective way for improving the energy efficiency and prolonging the network lifetime of WSNs. The CH failure causes the connectivity and data loss within cluster. It also disconnects cluster members from rest of the network. Hence, it is crucial to detect and recover the CH failure to maintain normal operation of cluster and network as a whole.

Bandyopadhyay et al. [8] proposed a multi level clustering scheme in multi hop fashion. It derives probability of becoming a CH that minimizes energy dissipation. These probability functions are highly complex and thus require numerical optimizations. It also gives the concept of forced CHs i.e. if a node does not fall within the range of any CH, it becomes a CH itself. Periodical run of clustering algorithm for load balancing is used here also.

In REED (Robust Energy Efficient Distributed clustering) [9], a k-fault tolerant (i.e., k-connected) network is constructed. In this, fault tolerance is achieved by selecting k independent sets of cluster heads on top of the physical network, so that each node can quickly switch to other cluster heads in case of failures or attacks on its current cluster head. The independent cluster head overlays also provide load balancing and security. In this, periodically re-clustering the network is done which consumes significant energy. Moreover, to maintain a list of k cluster heads list requires a lot of storage space.

In EEMC (An Energy Efficient Multi Level Clustering) [10], CHs at each level are elected on the basis of probability function which takes into consideration the residual energy as well as distance factor very efficiently. In this scheme whole information is sent and received by sink node for cluster formation. Fault tolerance is provided by periodic re-clustering of whole network.

In cellular approach to fault detection and recovery [11], network is partitioned into a virtual grid of cells, where each cell consists of a group of sensor nodes. A cell manager and a secondary manager are chosen in each cell to perform fault management tasks. Secondary manager works as back up node which will take control of the cell when cell manager fails to operate. This protocol handles only those failures which are caused by energy depletion.

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FTEP [12] is a dynamic and distributed CH election algorithm with fault tolerance capabilities based upon two-level clustering scheme. If energy level of current CH falls below a threshold value or any CH fails to communicate with cluster members then election process is started which is based on residual energy of sensor nodes. This election process appoints a CH and a back up node to handle CH failure. It has a single point (back up node) to detect failure which may itself be disastrous.

III. System Model

In this paper we extended our previous work [13] for fault detection and recovery protocol for two –level clustering.

A. Network Model

Figure 1 shows the two-level clustering network model that used. *Various symbols and terms used are shown in Table I.* All sensor nodes are homogeneous, which have two transmission modes i.e. high power transmission mode for communication between CHs and BS and low power transmission mode for communication between cluster members and CH. The distribution of sensor nodes is uniform throughout the environment. Communication medium is radio links. Links between two sensor nodes is considered bidirectional. There is only single channel for communication between sensor nodes.

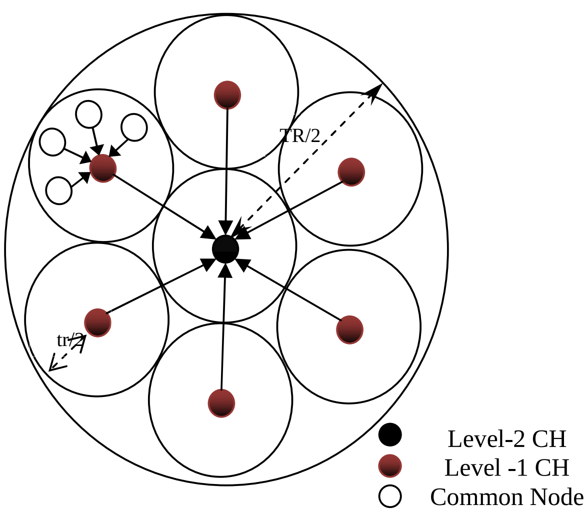

Figure 1 Network Model

During the network deployment, all the sensor nodes are assigned same initial energy value. All sensor nodes are assumed to know their geographical location [14]. We assume that clusters may overlap during election procedure so that every sensor node comes under at least one cluster. Initially, some sensor nodes are randomly selected as CHs and they announce their energy levels and location information. These CHs start working in high power transmission mode while other regular sensor nodes work in low power transmission mode.

B. Sensor Node's Energy Model

A sensor node consists of sensors, analog signal conditioning, data conversion circuitry, digital signal processing and a radio link. Each component of sensor node consumes energy for sending and receiving data. The following energy consumption model shows the energy, consumed by components of sensor node.

Assuming path loss, the energy consumption on each sensor node is:

$$E_{tx} = \left(e_{tx} + e_{amp} \times d^2\right) \times b$$
$$E_{rx} = e_{rx} \times b$$

According to eq. 1, the transmitter unit consumes energy to send bits; where e_tx the energy is consumed by transmitter electronics per bit and is the energy used by amplifier per bit. According to eq. 2, the receiving unit consumes energy to receive bits, where is the energy used by receiver electronics per bit.

TABLE I
NOTATIONS USED IN PAPER

d	Distance that message travels
b	Number of bits in the message
e_{tx}	Energy dissipated in transmitter electronics per bit (taken to be 50nJ/bit)
e_{amp}	Energy dissipated in transmitter amplifier (taken to be 50nJ/bit)
e_{rx}	Energy dissipated in receiver electronics per bit (taken to be 50nJ/bit)
E_{tx}	Energy consumed in transmission
E_{rx}	Energy consumed in receiving
SV	Status vector
Loc_i	Location of node
CH_i	Cluster head of cluster
c_i	Cluster
$e_{n_i}^{curr}$	Current energy of node
e_1^{max}	Energy level at which sensor node can participant in election of at level-1
$e_1^{min'}$	Energy level at which current starts election process at level-1
$e_1^{min''}$	Energy level up to which election process must be completed at level-1
e_2^{max}	Energy level at which sensor node can participant in election of at level-2
$e_2^{min'}$	Energy level at which current starts election process at level-2
$e_2^{min''}$	Energy level up to which election process must be completed at level-2
$tr/2$	Transmission range of node at level-1
$TR/2$	Transmission range of node at level-2

Table I summarizes the meaning of each term and its typical value. The values for e_1^{m}, e_1^{m}, and e_1^{mi} are updated during each election process at level-1. Typically, value of e_1^{m} for next election round is set to the average value of the energy levels of all candidate nodes during current election round.

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The values of e_1^{mi} is set according to e_1^{m}. The values of e_1^{mfi} is set according to e_1^{mi} as follows:

$e_1^{mfinr} = e_1^{m}$ - (energy consumption during election process + energy consumption in data transmission during that period)

These values of e_2^{m}, e_2^{m} and e_2^{mi} calculate similarly for cluster at level-2.

IV. FTTCP Protocol

FTTCP works in two phases namely: setup phase and steady state phase. Setup phase runs only once, when network starts working. In setup phase, clusters are formed and remain fixed through-out the lifetime of network. Steady state phase consists of three phases: CH election, failure detection and failure recovery. Failure detection runs parallel with network operation.

A. Setup Phase

Clusters are formed only once during the setup phase before the network starts to run (as shown in Figure 2). Here we explain only level-2, level-1 explained in [13]. After the formation of clusters at level-1, some CHs are randomly selected as a CH for level-2, because energy of each CH at level-1 is equal in amount. CHs send advertisement messages that contain energy and location information of CHs to neighboring CHs (at level-1). Each CH that listen to this advertisement message responds with a return message comprising its residual energy and location. However, a CH may be in the range of multiple CHs, but finally it must be associated with a single CH(at level-2). If any CH falls within the overlapping region of more than one CH, it decides its association to a CH by calculating the value of e/d (energy/distance). CH (atlevel-2) that has maximum e/d value is selected as final CH by that CH. If more than one CH yields same maximum e/d value, then any of them is randomly selected. If a CH does not fall within the range of any CH, it declares itself as a CH and gets activated in high power transmission mode. When clusters are established, the CHs (at level-1) collect the data from cluster members, perform local data aggregation and send it to CH of level-2. This CH sends data to base station or sink node in multi-hop manner.

Clusters form circle of radius size at level-1 and at level-2. and size is taken to confirm that every node in cluster able to communicate with other nodes within a single-hop in same cluster.

B. Steady State Phase

Once cluster is formed, CH creates a TDMA schedule for cluster members and sends it to them at both levels. Cluster members sense data and send it to CH according to TDMA schedule. This process continues for all clusters until CH's current energy level equals to or less than or CH fails. Then CH starts election process of new CH for next round or recovers from failure respectively (as shown in Figure 3).

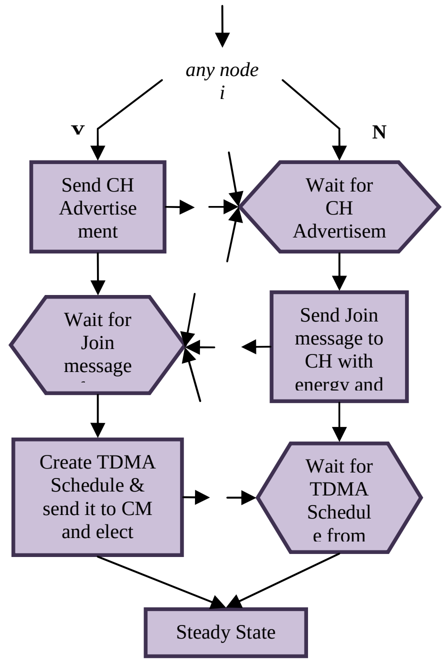

Figure 2 Setup Phase

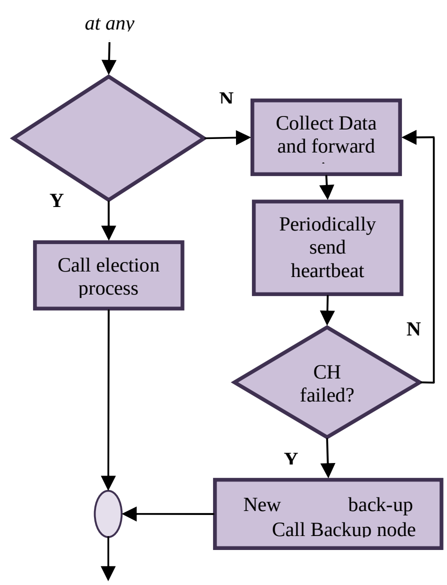

Figure 3 Steady State Phase

CH Election

CH broadcasts e_i^{max} for next round, which is average energy of those cluster members who participated in last election process. All cluster members within cluster listen message and compare with their current energy level (e_{ni}^{crnt}). cluster members which have e_{ni}^{crnt} greater than or equal to e_i^{max} , marks itself as a participant for election process(as shown in Figure 4). All participant sensor nodes broadcast their and location. All participant cluster member can listen to each other because all cluster

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members are within low (at level) or high (at level-2) power transmission range of each other. Because of this, all participant sensor nodes know about and of each other. Hence, each participant cluster member is aware about higher energy participant cluster member. The participant cluster member with highest value of promotes itself as CH and gets activated in high power mode (at level-1); whereas cluster member with second highest energy upgrades itself as back up CH. New CH receives and of all participant cluster members during election process, it calculates average of all and gets value of , which is used for next round. Both new CH and back up node know the value of . All participant cluster members mark themselves as non-participant cluster members again. The previous CH also starts working in low power mode (at level-1).

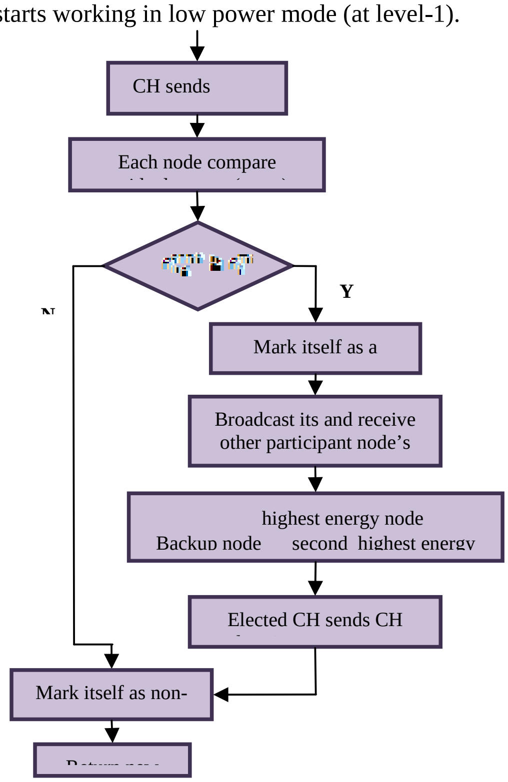

Figure 4 CH Election

Failure Detection

The detection process runs parallel with normal network operation by periodically performing a distributed detection process at each cluster member (as shown in Figure 5). For failure detection mechanism each cluster member maintains a status vector and a timer. In status vector each bit corresponds to a cluster member. Initially all bits are set to zero of status vector on each cluster member. A bit in the vector is set once its corresponding cluster member detects that CH has failed. CH of each cluster periodically sends a hello message (i.e. notification that CH is alive) to cluster members after a certain time interval. Cluster members also know about time interval, CH sends it to cluster members. After that time interval cluster member, who does not listen hello message, sets its corresponding bit as one in status vector and locally decides that CH has failed and broadcasts data plus status vector. Other cluster members also listen this message. They extract status vector from message and merge it with own status vector and this process continuous up to the end of the TDMA schedule. At the end of the TDMA frame, cluster members reach on an agreement about failure of CH. If all bits of status vector are set then it is decided that CH has failed.

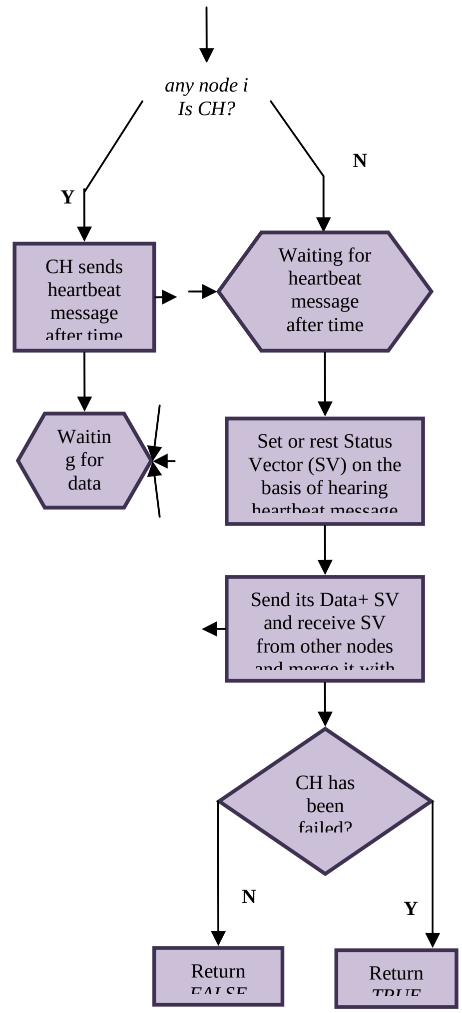

Figure 5 CH Failure Detection

Failure Recovery

By using agreement protocol when cluster members confirm about CH then cluster member who has last slot in TDMA schedule informs to back up node about failure. Back up node elects itself as a CH by sending an advertisement message in high power transmission mode (as shown in Figure 4). It keeps on working as CH till its residual energy level reaches a critical limit or it fails. New back up node is required for new CH depending on application, so CH start election process for new back up node by sending. Back up node election process is similar to election process of CH.

V. Performance Evaluation

A. Simulation Environment

In this section, we evaluate the performance of our proposed FTTCP protocol. We used OMNET-4.0 [15] as simulator and same radio model as discussed in section III. The basic simulation parameters are given in Table II.

TABLE II
EXPERIMENT PARAMETERS

Parameter	Value
Area of sensor field	100×100 m^2
Sink position	At origin (0,0)
Initial energy per node	1 J
Path loss exponent	2
ϵ_{tx}	50 nJ/bit
ϵ_{amp}	100 pJ/bit/m2
ϵ_{rx}	50 nJ/bit
Size of data packet	500 bits
Size of control packet	20 bits
Sensing Interval	0.5 s
High transmission range	60 m
Low transmission range	20 m
No of Nodes	300
Cluster Size	10, 20, 30

In order to check the performance of FTTCP protocol, we take following metrics/clustering attributes:

- *Network lifetime*: This metric gives the time up to which a network remains alive. It shows number of rounds (including fault tolerance) up to which network remains alive for different number of nodes in network. One round consists of an operation of network from sensing the phenomenon to receiving data at sink node including election process and fault handling if any.
- *CH election overhead*: It is defined as energy consumed in electing a CH in a network. It is the energy consumed by total number of messages exchanged among sensor nodes for electing CH.
- *Detection Accuracy:* It shows how accurately fault can be detected by nodes. The detection accuracy is defined by the probability of false alarm, which is the probability that an operational CH is mistakenly detected as a faulty one. Detection accuracy performance is measured under different packets loss rates and cluster sizes.

B. Simulation Results and discussion

To find out more reliable and accurate results, we executed FTTCP protocol with different number of nodes, number of times and failure frequency.

Network lifetime

It can be observed form Figure 6 that as the number of nodes increases, network lifetime increases. But after certain number of nodes, the network life time starts decreasing due to more overhead of cluster maintenance. FTTCP consumes more energy in failure detection and recovery as compare to FTEP. Thus, it reduces average 0.42% number of rounds as compare to FTEP. When number of nodes are 100, network is alive up to 860 rounds.

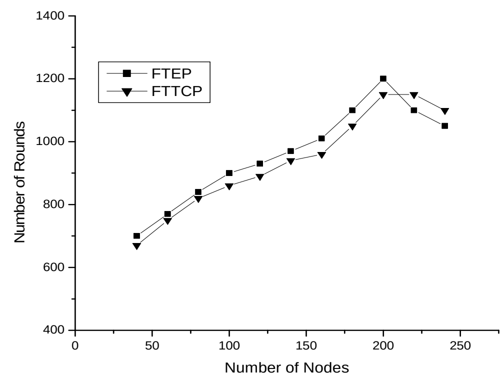

Figure 6 Network Lifetime

Detection Accuracy

From Figure 7, we can observe the effects of the packet loss rate on detection accuracy for different cluster size. For simulation, we consider the packet loss rate range from 0.2 to 0.4. It can be observed that with the increase of the packet loss rate the probability of false alarm positive increases, which leads to lower detection accuracy. A larger number of sensor nodes lead to a smaller probability of false alarm positive, i.e., higher detection accuracy. As expected FTTCP can achieve high detection accuracy.

CH election overhead

When number of nodes are 200, node failure frequency is 1% after every 50s for FTEP and FTTCP. It can be observed from Figure 8 that FTTCP consumes slightly more energy (average energy consumption 0.64%) for CH failure recovery as compared to FTEP. This is because of similar to FTEP, FTTCP elects back up node as new CH and also elects new back up node for new CH which results into more number of messages exchanged. In FTEP, back up node is not elected for new CH.

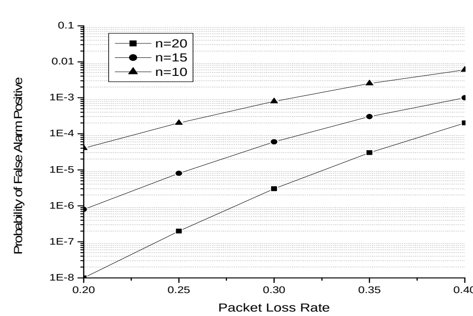

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Figure 7 Detection Accuracy

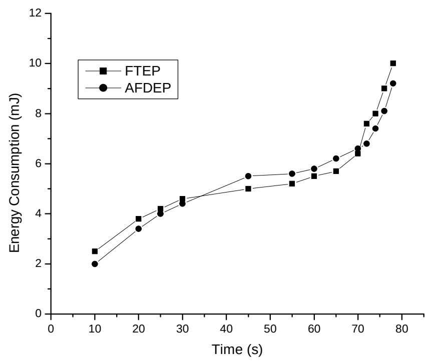

Figure 8 CH Election overhead

VI. Conclusion

FTTCP is agreement-based fault detection and recovery protocol for faulty CH for two level clustering in WSNs. FTTCP periodically checks for CH failure. This detection process runs parallel with network operation. It provides high accuracy, because it allows each cluster member to detect its faulty CH independently. It employs a distributed agreement protocol to reach an agreement on the failure of CH among multiple cluster members. In order to recover from faulty CH, back up node is elected as new CH and new back up node is elected locally. Election of CH and back up node is based on residual energy of sensor nodes. A simulation result show, however, FTTCP consumes little bit more energy than FTEP, but provides high detection accuracy in harsh environment.

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